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# Assessment of Well Integrity at Nagaoka $CO_2$ Injection Site Using Ultrasonic Logging and Cement Bond Log Data

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**Abstract**

This paper reports logging results for well integrity conducted at the $CO_2$ injection site in Japan. Well integrity is one of the essential issues for safety in geological $CO_2$ storage. Wells in the Nagaoka site have been used for monitoring logging of $CO_2$ behavior for more than ten years, and have experience of large earthquakes near the site. Time-lapse ultrasonic and cement bond logging have been employed to investigate the well integrity of the observation wells. Results of the ultrasonic logging showed that there was no sever damage or deformation in the casing at the reservoir depth. No clear change in cement can be seen in either logging results, even at the depth where the cement was exposed to the $CO_2$. These results showed that there was no clear evidence of $CO_2$ leakage at Nagaoka.

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## 1. Introduction

For the safety of $CO_2$ sequestration, injected $CO_2$ must be trapped underground and not allowed to leak to the surface. Well integrity is one of the essential issues because wells and annuli in cement can act as leakage pathways for $CO_2$ from the reservoir to the surface [1]. Of the well components, the cement between the casing and formation will be the first material exposed to $CO_2$, and therefore, the state of the cement in a $CO_2$ rich environment has been studied (e.g., [2]). Because there are many different possible leakage pathways, it is necessary to use several methods to examine the condition of the casing and cement exposed to $CO_2$.

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At Nagaoka, the first pilot-scale $CO_2$ injection site in Japan, well integrity has been examined by ultrasonic and sonic logging. It is more than ten years since the wells were drilled and cased and in that time there have been relatively large earthquakes near the site. The wells have been logged eight times by cross-hole tomography [3], and twice using a cased-hole dynamic tester [4-5]. This paper reports on the methods employed at the Nagaoka site for assessing well integrity, and presents the results of time-lapse loggings.

## 2. Tools for measuring well integrity

In this section, two non-destructive tools for measuring well integrity are introduced. The tools need to be able to investigate the integrity of casing, cement, the bond between casing and cement, and the bond between the cement and the formation.

Cement bond log (CBL) is the one of the oldest sonic logging tools for measuring the cement bond of the casing. This tool transmits a signal to the casing and the formation and then observes the signal at receivers placed several feet above the transmitter. A wave train arriving at a receiver is a composite signal, formed from a superposition of waves that passed through the casing, cement, and formation in parallel but at different speeds. The amplitude and transit time of the first signal to arrive has information on the cement bond. The observed signal will have a large amplitude in a well with a poor bond, because less energy of the transmitted signal propagates to the formation. The waveform, which is usually shown by a Variable Density Log (VDL), can be used to distinguish the state of the cement bonding. However, both the amplitude and the VDL represent the radially averaged bond between the cement and the casing, and it is difficult to identify the locations of a poor bond from the result of a CBL. Furthermore, large amplitudes can appear at depths with fast formations and liquid-filled microannuli [6].

Ultrasonic tools have been used to investigate well integrity. These tools use ultrasonic waves to measure impedance with better resolution than normal acoustic tools, and acquire reflected signals from the same depth in order to obtain the impedance of the casing and cement from the same pass. Reverberation within the casing will be observed, as will energy leaks out of the casing. Analyses of the timing, amplitude and decay rate reveal the internal radius of the casing, the thickness of the casing, and the acoustic impedance of the materials of the well and cement. Most of the tools can image wells over 360 degrees by rotating the signal gate, and therefore, the specific pathways and/or de-bonded areas can be identified. Because of the high attenuation of the ultrasonic waves, the reflected signal from the interface between the cement and the formation becomes smaller.

Both methods have a different response in the presence of gases outside of the casing. There is no one tool that can investigate all possible leakage paths simultaneously. Therefore, a suite of measurements must be run in order to analyze fully the integrity of the wells.

## 3. Time-lapse observation at the Nagaoka site

### *3.1. Nagaoka CCS site*

Here we briefly introduce the information of the Nagaoka site related to well integrity (Details of the Nagaoka project were reported in [7]). Nagaoka is an onshore $CO_2$ injection site in Japan and has aquifers without oil or gas at the target reservoir for $CO_2$ injection. One injection well and three observation wells were drilled with a horizontal distance between the injection well and the closest observation well of 40 m at the reservoir depth. The reservoir interval in each observation well was cased with fiberglass-reinforced plastic (FRP) to enable induction logging for monitoring of the $CO_2$ behavior. The inner diameter of the FRP casing was 139.7 mm, and the average thickness of the cement between the casing and formation was about 40 mm. Class-A cement was used for fixing the casing to the formation. $CO_2$ was injected into a thin permeable zone at the depth of 1100 m, and the total amount of injected $CO_2$ was 10.4 kilotons during the period between 7 July 2003 and 11 January 2005. $CO_2$ arrival at two observation wells was detected about 240 and 340 days after $CO_2$ injection, respectively. These two observation wells have been exposed to $CO_2$ for more than eight years.

We have conducted time-lapse ultrasonic logging and CBL to verify the well integrity of the observation wells. Fig. 1 shows the timing of these loggings with a comparison of the resistivity change from the baseline measurement at the closest observation well. Note that the Nagaoka site has experienced two large earthquakes; the Mid Niigata Prefecture earthquake that occurred on 23 October, 2004 (Magnitude 6.8), and the Niigataken Chuetsu-oki earthquake that occurred on 16 July, 2007 (Magnitude 6.6). The hypocenters of both earthquakes were about 20 km distant from the Nagaoka site. The second and the third logging runs in Fig. 1 were performed after these earthquakes.

### *3.2. Results of ultrasonic logging at Nagaoka*

We conducted ultrasonic logging four times in ten years. For the first two observations, we employed Schlumberger's USI tool [8] with 0.5 MHz transmitting frequency, and for the latter two, we employed Advanced Logic Technology's ABI40 and ABI43 tools [9] with 1.2 MHz transmitting frequency. At each logging, the fluid properties inside the casing were measured in order to calibrate the results of the ultrasonic measurements.

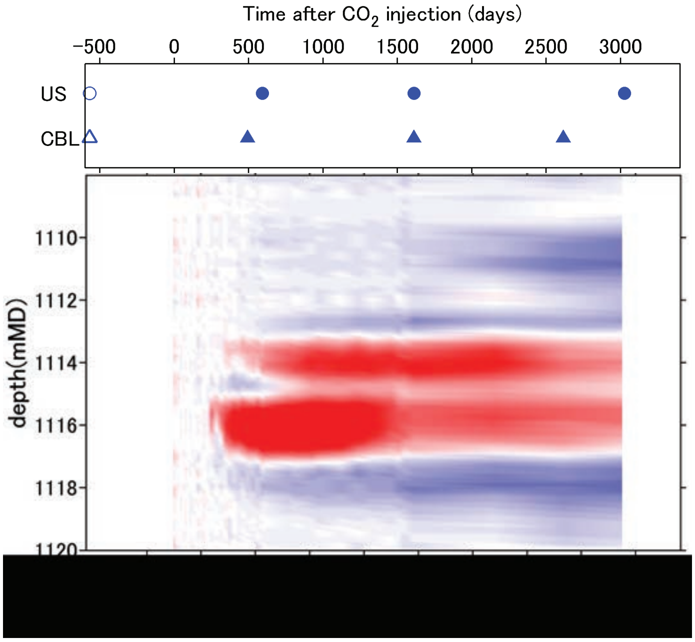


Fig. 1. Timing of ultrasonic logging and CBL at the Nagaoka site. The lower panel represents the temporal change of the resistivity from the baseline.

Fig. 2 represents the results at the reservoir depth of the most recent logging. From the four left charts, the shape and thickness of the casing are obtained. Fig. 3 illustrates the shape of the casing at the depth of the joint of the iron and FRP casing. The amplitude of the first reflection at the part of the FRP casing was smaller because the impedance contrast between the FRP casing and water is smaller than that between the iron and water. The travel time of the first arrival at the FRP casing was shorter because of the thickness of the casing. Figs 2 and 3 reveal that the shape of the casing has not changed, and that there was little damage inside the FRP casing.

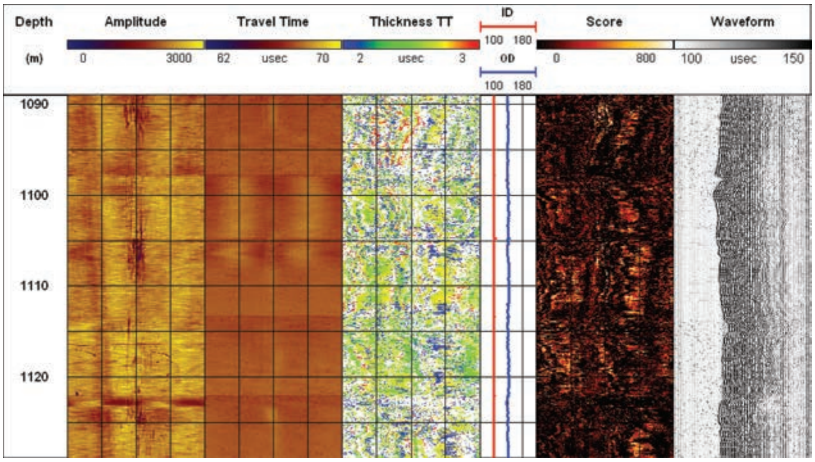


Fig. 2. Results of the most recent ultrasonic logging. From the left: amplitude of the first arrivals, travel time of the first arrivals, map for the thickness of the casing, radially averaged thickness of the casing, reliability of the measurement, and waveforms.

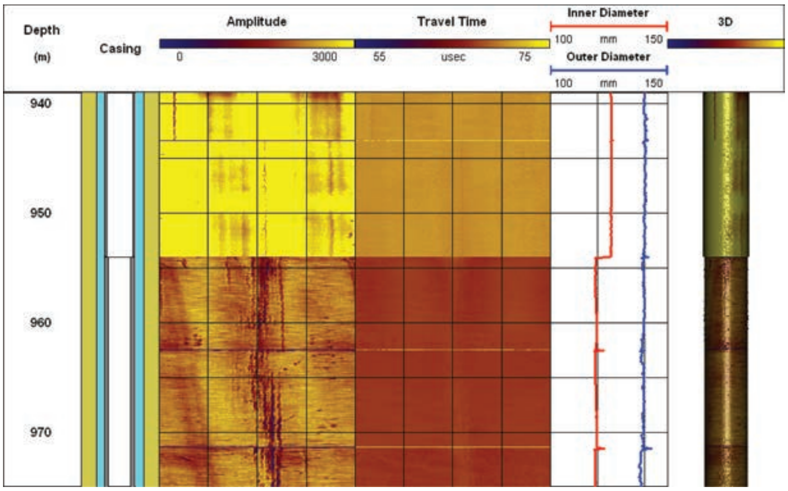


Fig. 3. The results of ultrasonic logging near the joint of the FRP and iron casing. From the left: amplitude of the first arrival, travel time of the first arrival, radially averaged inner and outer diameter of the casing, and 3D image of the casing.

We identified multiple reflections inside the FRP casing. Fig. 4a displays the differences of travel time and relative amplitude of the later signal derived from the waveform of the most recent measurement. The travel times of the multiple reflections were almost constant, although there was error in evaluating the time at the later time. The amplitude of the multiple reflections decreased as a function of the impedance of the casing, the cement, and borehole fluid. The relative impedance of the cement can be calculated from the decreasing ratio.

Fig. 4b represents the cement impedance map obtained from the loggings in 2001, 2005, and 2011. The resolution of the logging in 2011 was better because of the utilization of a higher frequency and A/D converters with higher resolution. Because the logging tool was different from the previous two measurements, the value of the cement map cannot be directly compared. However, the features of the pattern of low cementing were thought to be similar. Furthermore there is no evidence that the cement quality had become poorer. Note that the reflection from the interface between the cement and formation was not clear in the ultrasonic loggings at Nagaoka.

### *3.3. Results of CBL at Nagaoka*

We conducted CBL four times over ten years. The first observation was done using Schlumberger's CBL tool [8] and the latter two observations were done using Halliburton's Radial Cement Bond Log (RCBL) tool [10]. The amplitude of the first arrival was recorded using a receiver at 3 feet, and the waveform was acquired using a receiver at 5 feet above the transmitter.

Fig. 5 show the results of CBL obtained in September 2010 from the closest observation well. The amplitude of the reflected signal changed at the cement top (790m) and at depths where the casing type changed (iron to FRP:950 m, and FRP to iron:1205 m). The amplitude at the FRP casing part was smaller than that at iron casing. This is because of the difference of the material and thickness of the casing, which is consistent with the results of ultrasonic logging (Fig. 3). Although variable amplitude density (VAD) could represent the radial change of the amplitude, there is no clear difference in the cement bond radially at Nagaoka.

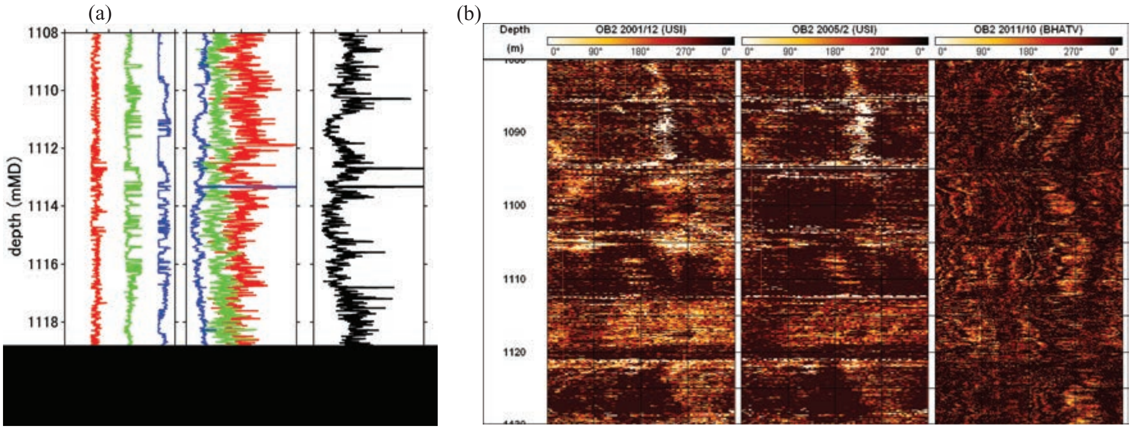


Fig. 4. (a) Information from the later signal of ultrasonic logging. From the left: travel time of multiple reflected wave from the first arrival, relative amplitude of the multiple reflections normalized by the first arrival, and decreasing ratio of the multiples. (b) Cement map obtained by the ultrasonic logging at cap rock and reservoir depth of the Nagaoka site. Lighter color shows low impedance suggesting low cementing or existence of gases.

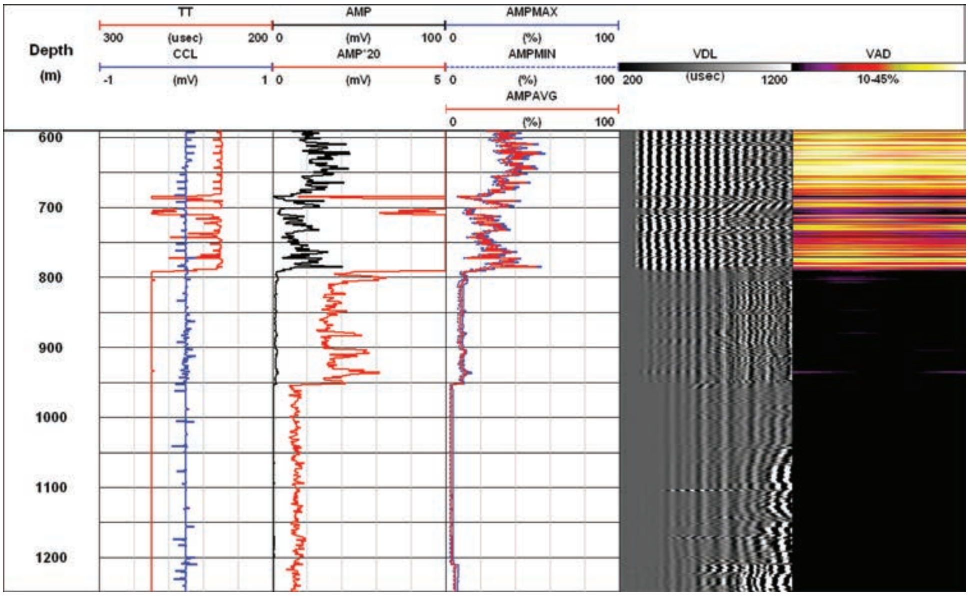


Fig. 5. Results of the most recent RCBL. From the left: travel time and CCL, amplitude, maximum and minimum amplitude among Variable Amplitude Density (VAD), VDL, and VAD map.

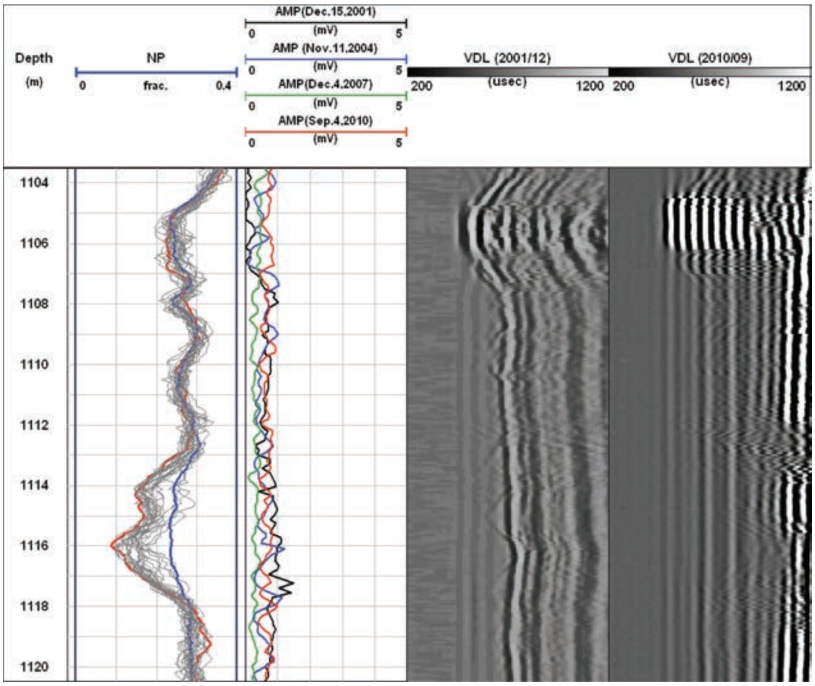


Fig. 6. Comparison of the temporal changes of neutron porosity (by monitoring loggings), amplitude of CBL, and VDL of the first and the most recent CBL.

Fig. 6 represents the time-lapse logging of neutron porosity, amplitude of CBL, and VDLs observed in 2001 and 2010. The results of neutron porosity reveal the existence of supercritical $CO_2$; however, the results from the amplitude of CBL are within the fluctuation of the measurement error. This result suggests that there is no clear evidence of degradation of the cement up to the point of the most recent logging, even if the cement has been exposed to $CO_2$ since February 2004.

The reflected signal from the interface between the cement and the formation can be observed with the moderate amplitude at around 800 micro-sec in the VDL. This reflection was clear in 2001, but it became vague in 2010. This could be explained by the existence of $CO_2$ in the formation. The impedance of rocks bearing supercritical $CO_2$ is smaller than that of water-saturated rock and thus, the impedance contrast between the cement and formation would become smaller. Cement near the formation was thought to be affected by $CO_2$. However, these physical and chemical changes near the interface did not reduce the bonding in Nagaoka, and thus, the cement was thought to be well bonded to the formation as well as to the casing.

## 4. Discussion

We have conducted sonic and ultrasonic logging to investigate the well integrity through the FRP casing. There was difficulty with data quality because the amplitude of the reflected signal becomes smaller than is the case with the iron casing. Despite these disadvantages, the cement map and cement bond has been evaluated, suggesting that the cementing was still fine ten years after drilling and eight years after $CO_2$ arrival.

In the ultrasonic logging, we could not detect the reflected wave from the interface between the cement and formation. Because the CBL-VDL has the reflection from the formation, we could extract more information about the cement by combining the results of both tools. The geometry of the source and receivers of these tools was different and therefore, some help by numerical calculations is necessary to obtain the geophysical parameter of the cement.

Monitoring logging suggested that the sonic velocity (Vp) in the formation with supercritical $CO_2$ decreased. However, this tendency was not clear in this geophysical investigation of well integrity. This implies that the change of Vp in the cement with supercritical $CO_2$ is small and/or supercritical $CO_2$ did not penetrate through the casing. To consider the latter case the geochemical reaction should be taken into account. Asahara et al. [11] conducted laboratory experiments investigating the chemical reaction between $CO_2$ and an experimental well comprising iron, Class-A cement, and sandstone. They found that the cement near the sandstone reacts with the $CO_2$, but its ions can make carbonates with reacting with ions from the sandstone. Furthermore, fine-grained cement could seal the pores of the sandstone. With these effects, $CO_2$ invasion into the cement was prevented within the limited depth of the interface between the cement and the sandstone. Another geochemical logging program at Nagaoka is the sampling of the formation water using CHDT [4-5]. This logging provides information on chemical reactions between dissolved $CO_2$ and minerals. This data could be used for interpretation of the state of the materials near the well.

## 5. Conclusions

We have conducted time-lapse ultrasonic logging and CBL to investigate the well integrity of the observation wells at the Nagaoka site. Analysis from the ultrasonic logging suggested that: (a) there is no severe damage or deformation in the FRP casing at the reservoir depth, (b) there is not much change of the casing thickness, and (c) there is no clear evidence that the cement impedance behind the FRP casing at the reservoir depth has changed. Results from the CBL indicated that: (a) the casing and formation were well cemented before the $CO_2$ injection, and (b) the cementation remains good despite being exposed to $CO_2$ for more than eight years, because the amplitudes of the first arrivals are almost constant. Furthermore there were large earthquakes near the site after the $CO_2$ injection; however, the log results showed no clear difference between the results obtained before and after the earthquakes. These results showed that there is no clear evidence of $CO_2$ leakage at Nagaoka, and support the safety of the practice of underground $CO_2$ storage.

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